An End-to-End Model of a Hall Thruster

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by

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13. ABSTRACT *(Maximum 200 words)*

The research has accomplished several goals: the development and implementation of realistic EP plume-wall interaction models, including tracking and deposition of sputtered material, simulation of the operator of a Hall Thruster in a vacuum tank, and the extension to the near-plume of a sophisticated Hall thruster transient hybrid PIC model which had been previously used only to describe the internal flow. The first two items have been described in detail in our previous yearly Report and in published papers and theses. This Final Report concentrates on the last item, the use of a transient PIC code for the plume.

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Abstract

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1. Introduction

The state of the art in modeling of plasma thruster plumes at the time this work was initiated was deficient in several aspects: oversimplified physical description of the plasma, sketchy models for plasma-wall interactions, inability to account for transient effects, and lack of flexibility in the specification of geometrical details. With the exception of the last item, which remains largely to this day, our research attacked all these areas using extensions of numerical codes previously developed by our group. Thus, the pioneering PIC-DSMC code of David Oh [6] was improved by S. Qarnain [2,3] by developing procedures for the generation of initial conditions from the output of thruster calculations using J.M. Fife's transient PIC code [7]. Qarnain also improved the model for calculation of sputtering yields by including Yamamura's incidence angle model [8]. This work was continued by B. Asare [4,5], who extended the sputtering data base to several materials, in part by utilizing the SRIM Monte-Carlo simulation of Eckstein et al [9]. Asare also surveyed and selected methods for prediction of the threshold energy for sputtering, an area of significant uncertainty, and of importance to our application, because many of the Charge Exchange (CEX) ions which impact spacecraft surfaces have energies in the threshold range. Finally, Martinez-Sanchez and Asare corrected and adapted the formulation of Yamamura[10] for the angular distribution of sputtered particles when the code indicates a wall impact and an ejection event is selected based on yield formulae; this work was partially carried out by M. Brenizer [11], and recently completed by S. Cheng [12]. Asare used various versions of these models to carry out computations of the

effect of including a shroud around a Hall thruster for the purposes of limiting large-angle ion flux. It was found that if the shroud is long enough to block the view of the engine's core, there is a significant reduction of the flux, although some secondary effects arises from the resulting increase of the neutral density, and hence of the CEX activity.

2. *Refined Physical Modeling of the Plume*

All of this work (reported in Ref. [1]) was still based on the basic code of D. Oh, and thus suffered from the very simplified physical model it uses: magnetic confinement is neglected, electrons are assumed to follow the Boltzmann equilibrium density distribution, at a constant, prescribed temperature, and steady state is assumed. On the other hand, the independently developed code of Fife [7], although it is still a hybrid model (fluid electrons), does not suffer from these limitations: cross-$\vec{B}$ field diffusion is included, electrons satisfy a full set of momentum and energy equations, and (by using MCC rather than DSMC methodology for ionization) it is able to track transients on the ion time scales. Fife's code, on the other hand, was limited to the internal parts of the engine and its immediate vicinity, and did not include calculation of CEX ion production. It had been used, starting with Qarnain, as a tool for generation (after time-averaging) initial conditions for D. Oh's plume code, but not for the plume itself.

The task of extending Fife's transient code to the plume was partially accomplished by M. Brenizer in his Master's Thesis [11]. Brenizer added a MCC module for the calculation of CEX ion production; the DSMC methodology which D. Oh used in his code is much more computationally burdensome, and is not justified in our application, because only a small fraction of all ions undergo CEX collisions.

The formulation in Fife's model assumes that the electron temperature T_e and the modified potential $\phi^* = \phi - \frac{kT_e}{e}\ell n\, n_e$ are constant along each magnetic streamline, but vary from streamline to streamline. This dominance of magnetic effects is reasonably accurate in the high B field regions of the thruster, as we have verified using the even more detailed full PIC code of Szabo [13]. On the other hand, as D. Oh argued in his original work [6], magnetic effects lose importance a few diameters beyond the exit plane, and, in addition, the thruster's own field

gradually merges with and eventually is dominated by the geomagnetic field. For these reasons, Brenizer limited his extension of Fife's approach to the first two diameters beyond the exit plane. Even so, he was able to obtain a number of new and detailed insights on this very important region, where most of the CEX activity occurs. We will present here a selection of these results, and refer the reader to Brenizer's Thesis (Ref. 11) for additional detail. The calculations referred to a SPT-70 thruster, as in the experimental work of Fife.

The relative importance of ionization and charge exchange can be seen in Fig. 1, in a one-dimensional sense. Ionization dominates inside the engine, and also (contrary to most plume model assumptions) for an additional distance of the order of the mean radius. It then drops rapidly in the external expansion zone, while charge exchange remains about constant, and dominates eventually. The two-dimensional detail is illustrated in Figs. 2 and 3. It appears from these results that one cannot use a "frozen" model for the plume computation, unless the starting point is about one diameter past the exit plane.

The reliability of the constant Te assumption can be judged from the results in Fig. 4. Once again, the isothermal assumption can at most be used a few diameters downstream of the exit.

The thruster is known to operate in an oscillatory mode, with ionization cycles which introduce deep current modulations. This is shown by the simulation results in Fig. 5. The computations of Brenizer also allow us to assess the unsteadiness level at various points in the flow field. For example, Fig. 6 shows the potential fluctuations as they would be observed by an emissive probe located 3.5 cm downstream of the exit, and at three radial locations (outside the plume, top panel, directly in front of the exit, middle panel, and near the thruster's axis, lower panel). Similar information, but related to the electron temperature, is shown in Fig. 7. Only in the direct stream is the temperature observed to fluctuate at all. Finally, Fig. 8 shows plasma density at the same locations.

As was noted before, charge exchange does occur inside the thruster at a rate which, although dominated by ionization, is of the same order as that outside the thruster. This is ignored by all existing plume codes . To assess the effect, we can collect all CEX ions produced with various velocities, and classify them by

whether they formed inside the acceleration zone (AZ) or in the plume. This is shown in Fig. 9, where primary ions are also shown. The CEX ions formed in the acceleration zone end up being indistinguishable from the primary ions, since they accelerate through similar potentials after their formation. The externally formed CEX ions are clearly less energetic. Note that the maximum radial velocities are not much less than the axial velocities, indicative of a high divergence angle. Better discrimination is obtained if we collect only those ions which hit the "back plate", i.e., the extension of the exit plane of the engine. This is shown in Fig. 10; the internally formed CEX ions are seen to be in general less energetic at this point than those primary ions which arrive there (the black dots). The fact that some positive axial velocities are seen is due to the "back plate" being in fact a conical surface close, but not coincident with the exit plane.

Figure 10 gives no information on the geometrical distribution of the ion impacts on the "back plate". This is given in Fig. 11, and their energy distribution is in Fig. 12. The bulk of the impacting flux occurs in the first one or one and a half diameters, and most of the particles that hit have energies around 40 eV, although a medium-energy tail does exist as well.

To conclude this survey, we show three representative ion energy histograms that illustrate the evolution of the energy distribution shape as one moves from near the axis to the periphery or the outside of the plume. Figs. 13, 14 and 15 show these distributions at a distance of 17 cm. from the thruster exit, and for three angular ranges. Near the axis, energies about 250 eV predominate, with a low-energy tail. At about 50 degrees from the axis, a second peak at about 120 eV appears, and for angles around 80 degrees, this second peak alone survives.

3. Conclusion

The work discussed here has raised as many issues as it has resolved, and it is clear that much refinement remains to be introduced into Hall thruster plume models in the future. It is hoped that the tools we have developed and the explorations we have performed will be of use in that future work.

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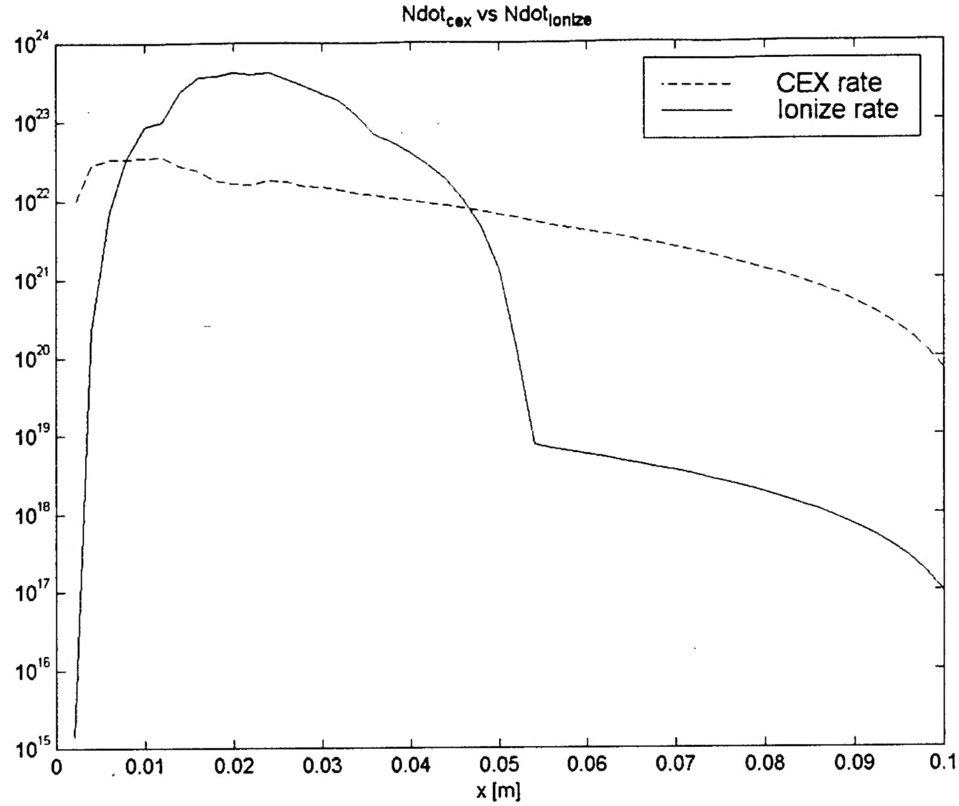

Fig. 1 Cross-section averaged charge exchange and ionization rates . Engine exit at x=0.025 m

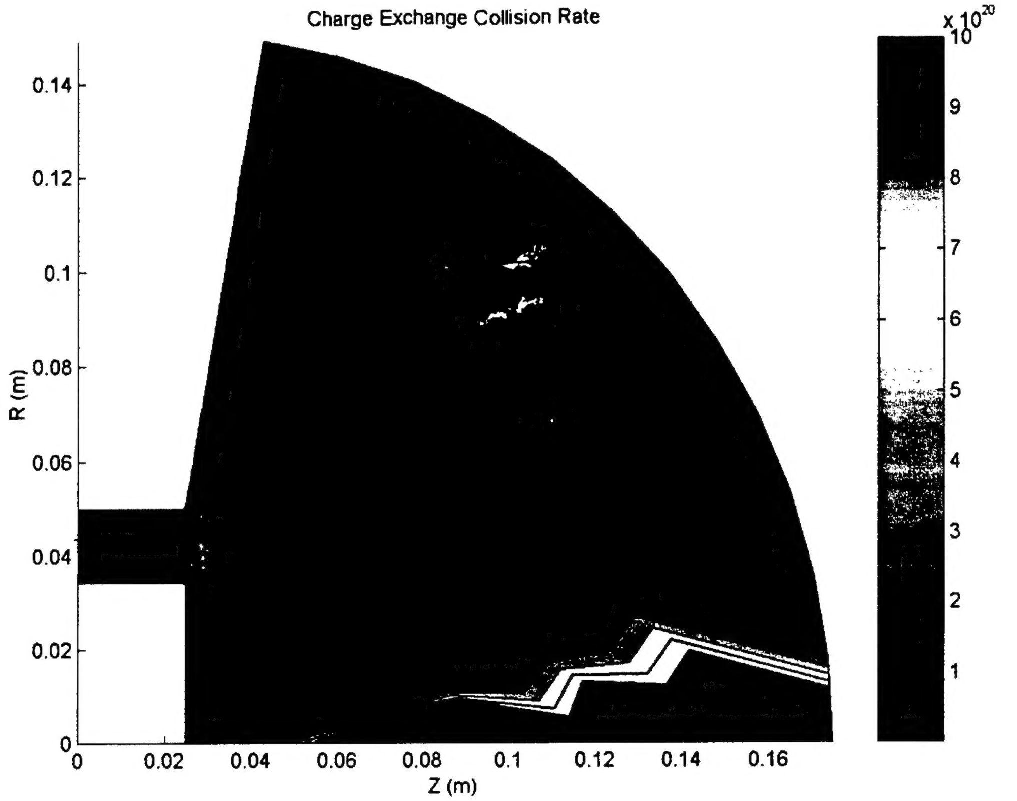

Fig. 2. Charge Exchange rate (m-3/s) in the near plume

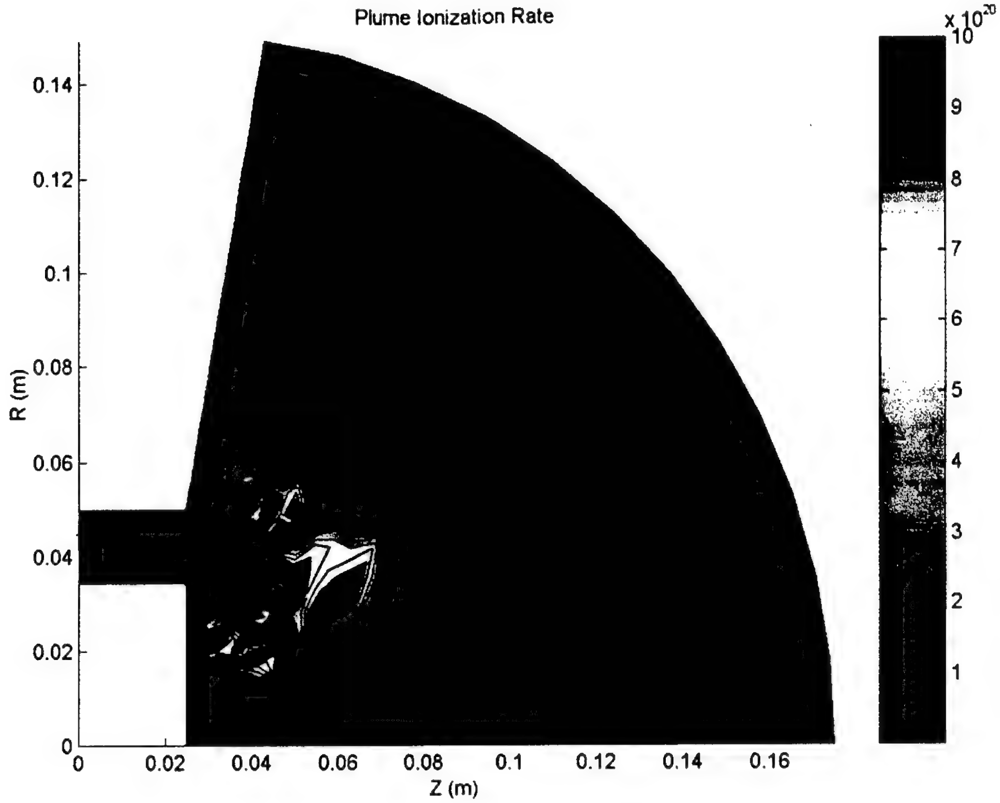

Fig. 3 Ionization rate (m-3/s) in the near plume

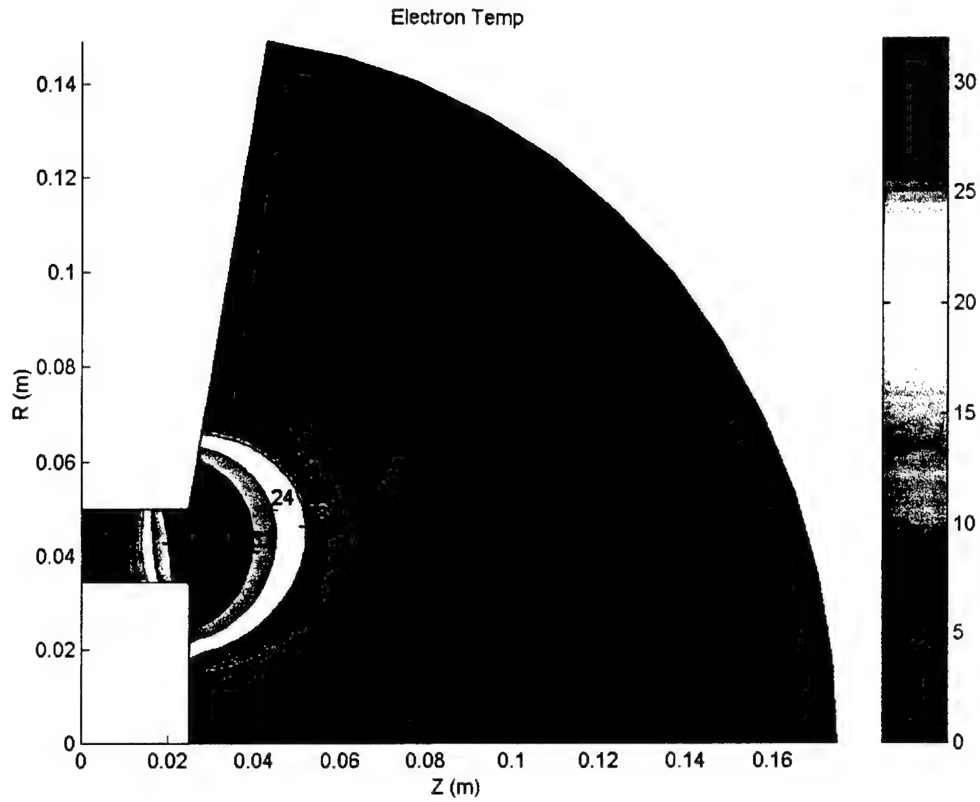

Fig. 4. Electron Temperature (eV) in the near plume

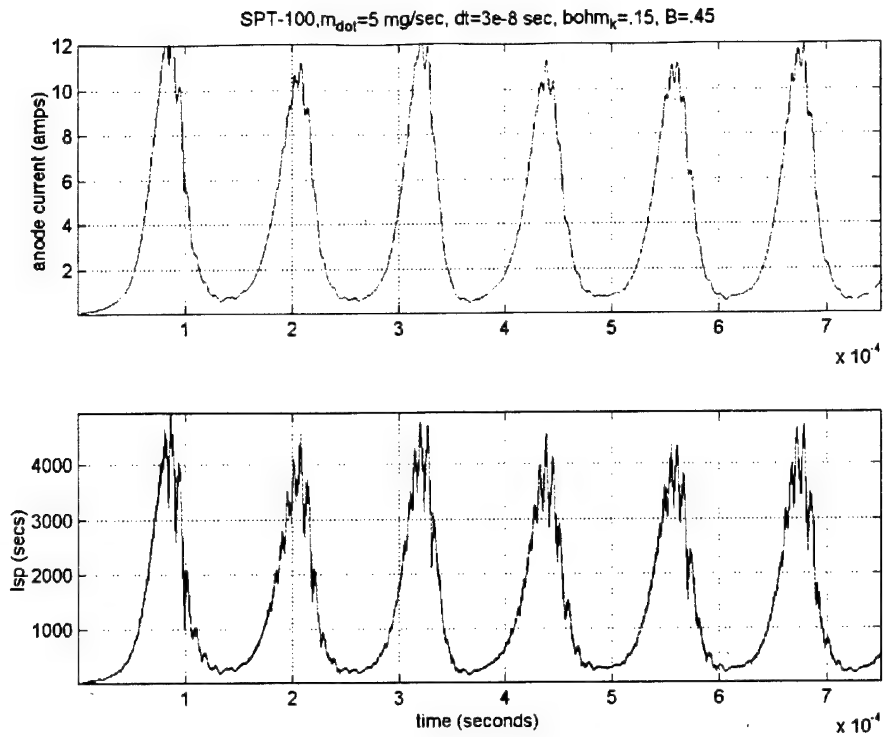

Fig. 5 Anode current and Isp for Hall thruster simulation

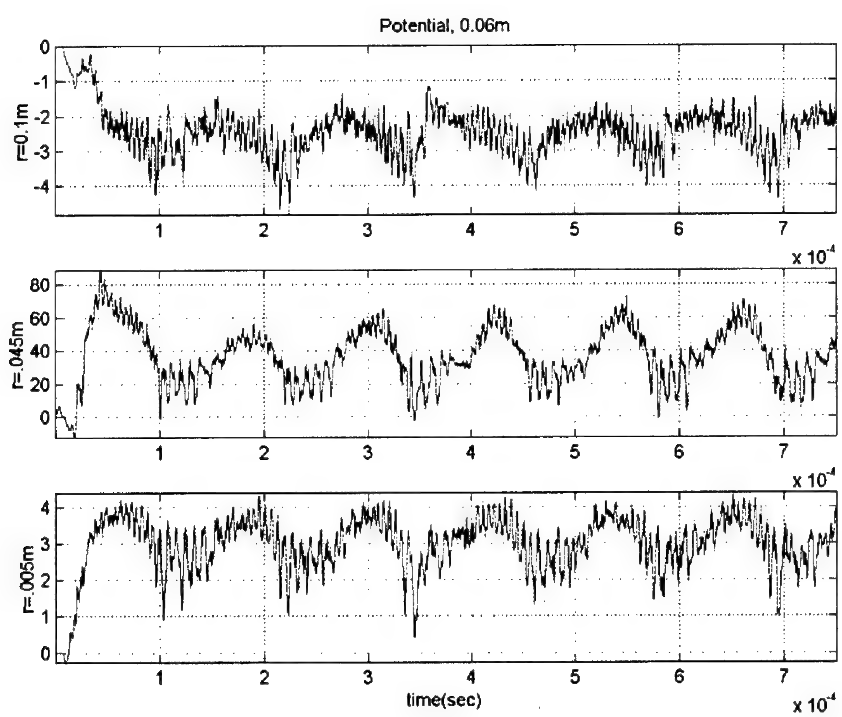

Fig. 6 Potential vs. time, 0.035 m from exit plane

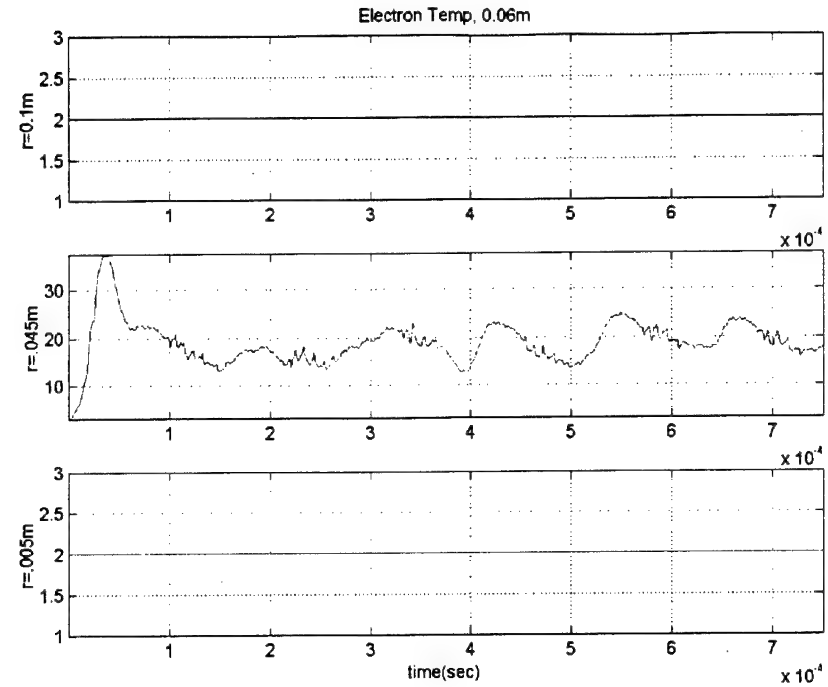

Fig. 7 Electron temperature vs. time, .035 m from exit plane

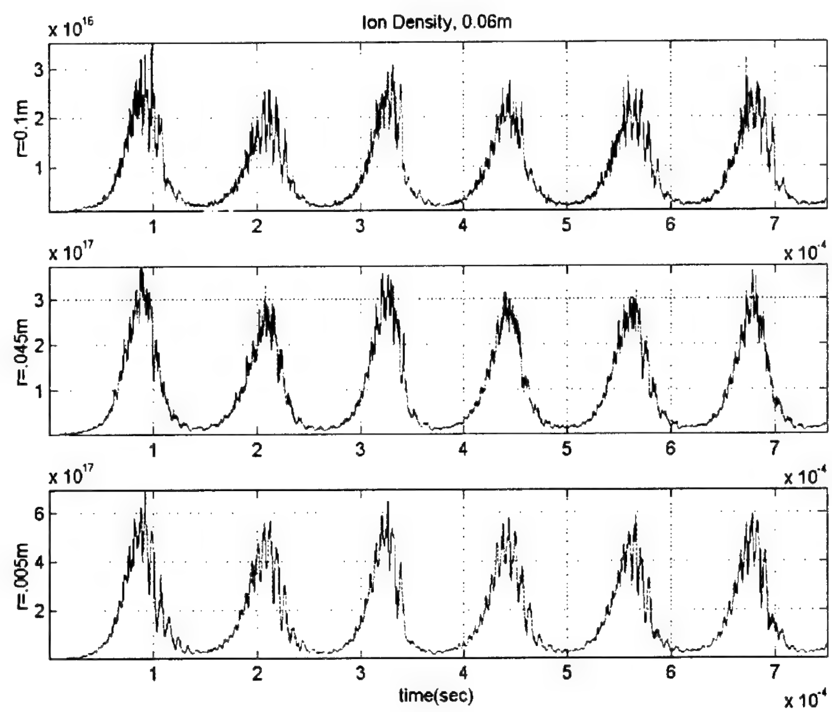

Fig. 8 Ion density vs, time , 0.035 m from exit plane

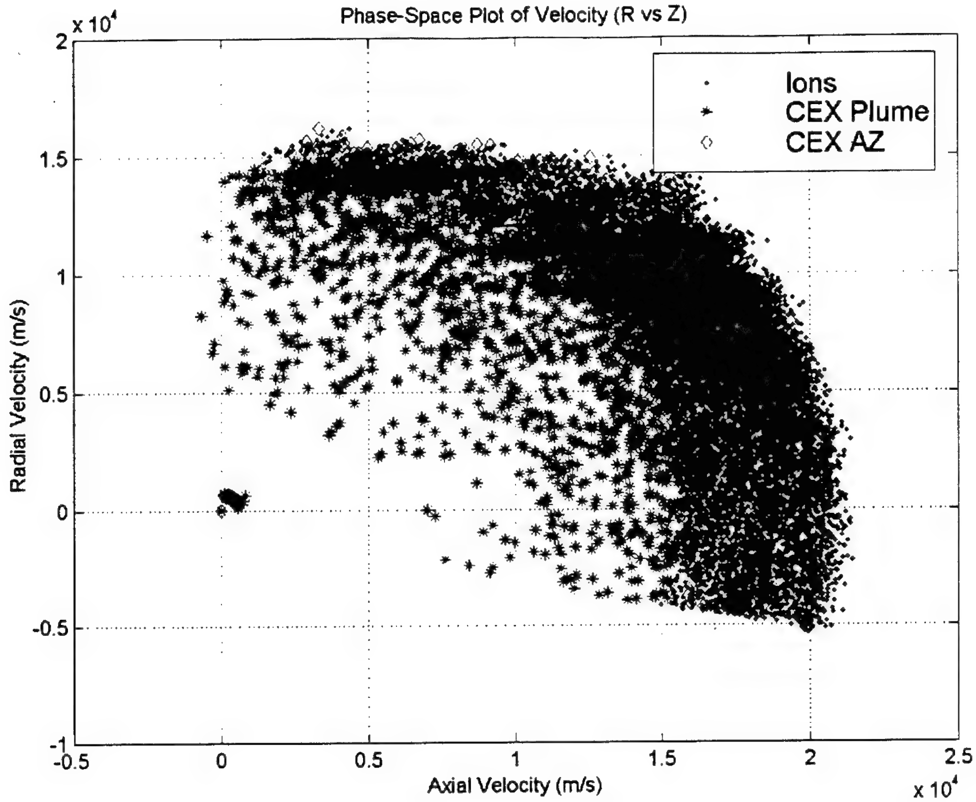

Fig. 9 Velocity phase-space plot for ions in the plume

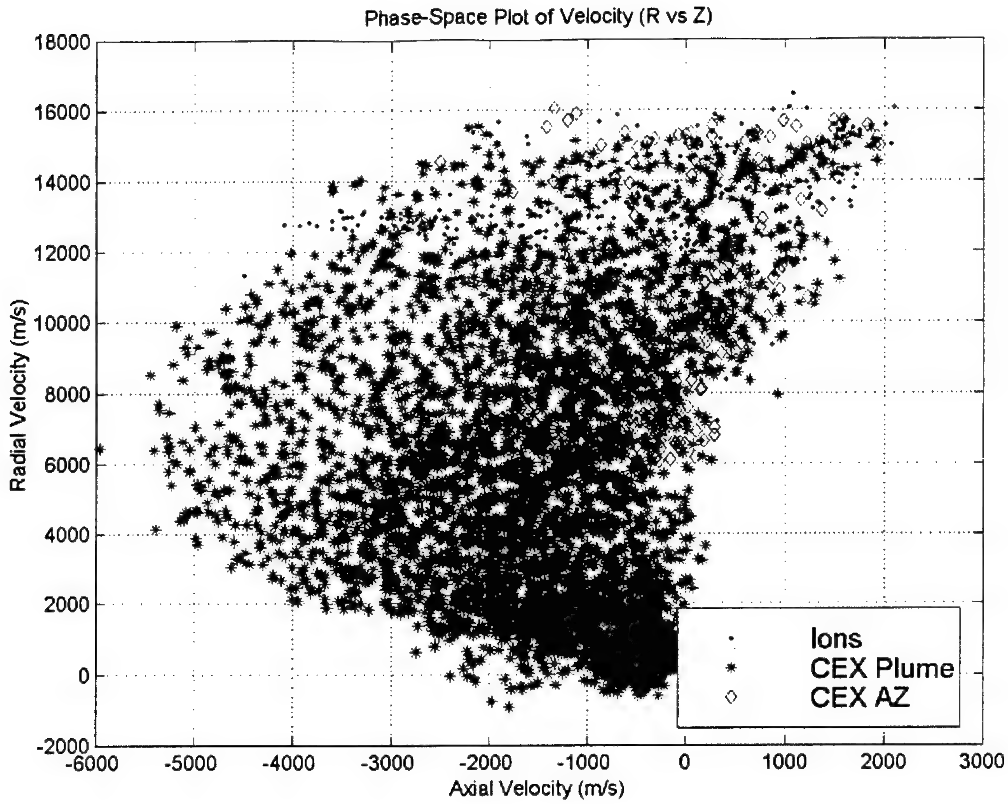

Fig. 10 Velocity phase-space plot for ions in the back-flow region

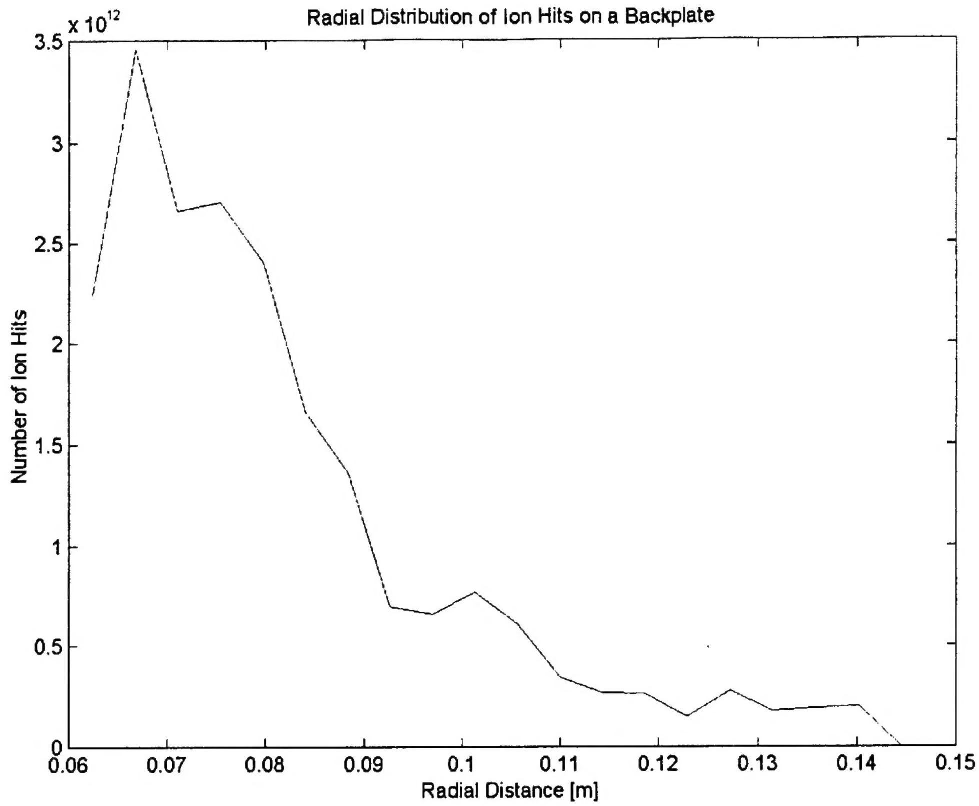

Fig. 11 Distribution of hits along the a radial "back plate" (1.5 E-5 sec)

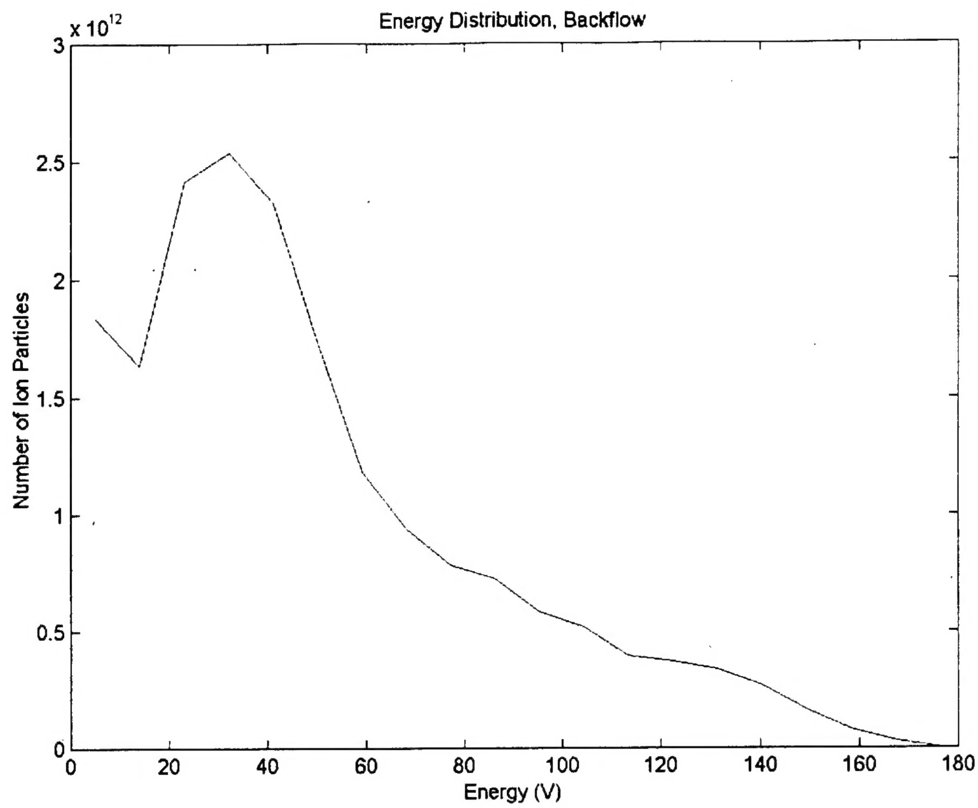

Fig. 12 Energy Distribution in the back flow region (1.5 E-4 sec)

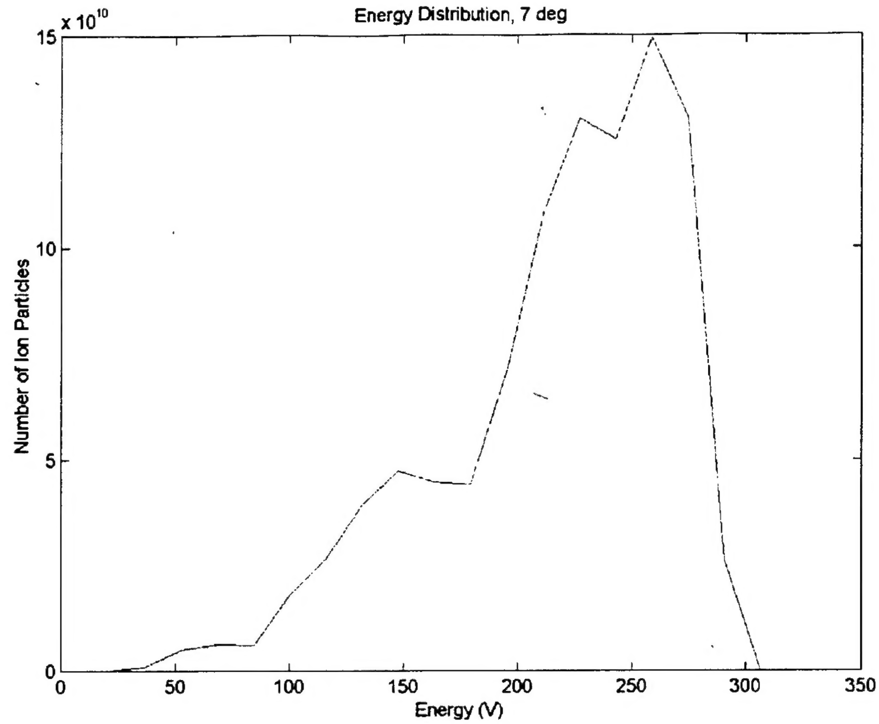

Fig. 13 Plume Energy Distribution, 0-7 degrees off-axis (no. of particles per cell)

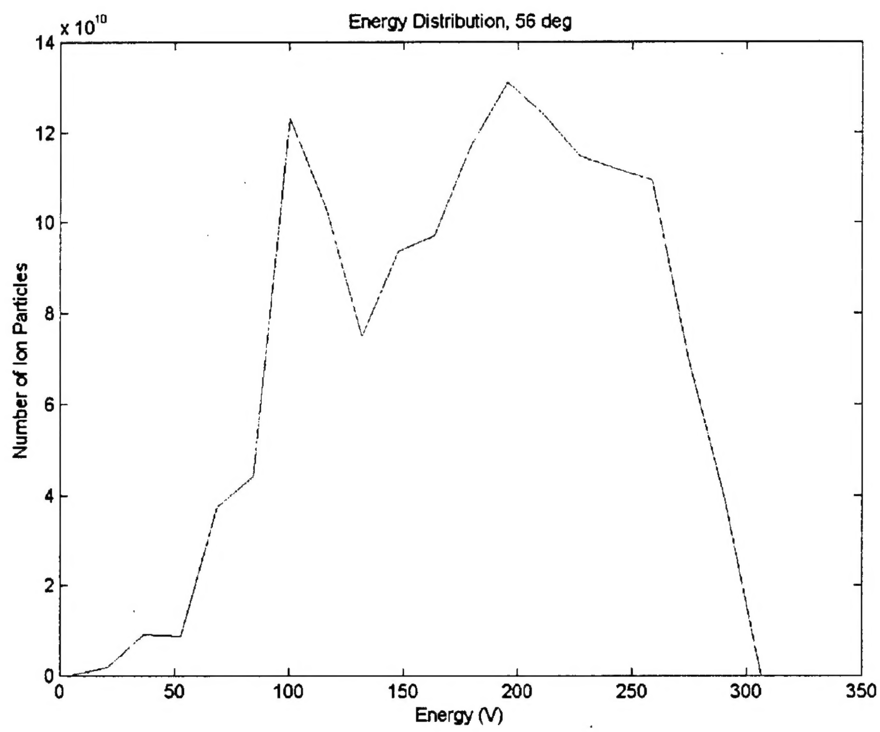

Fig. 14 Plume Energy Distribution, 49-56 degrees off-axis (no. of particles per cell)

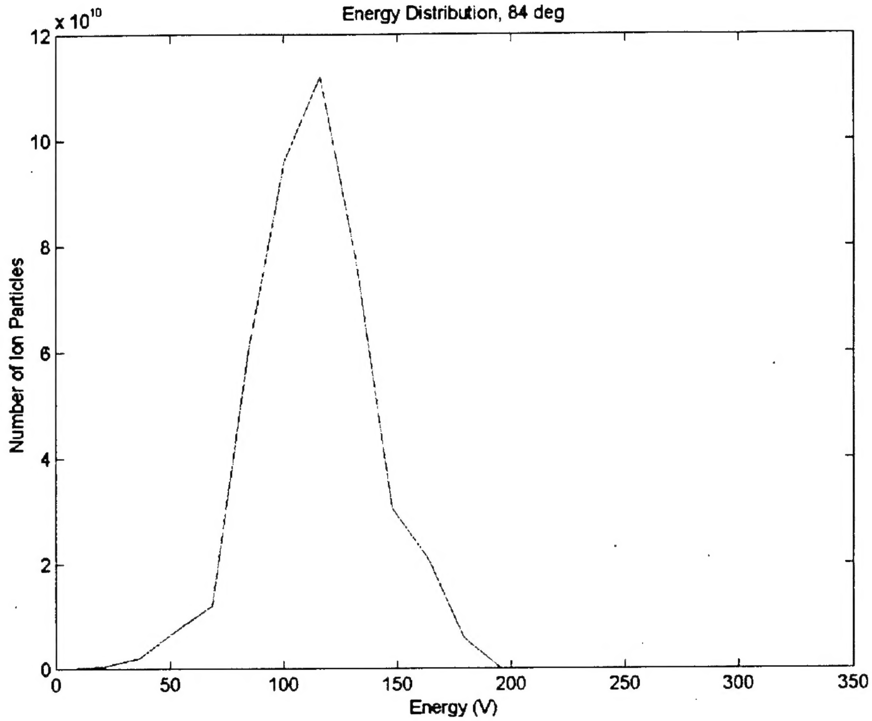

Fig. 15 Plume Energy Distribution 77-84 degrees off-axis (no. of particles per cell)